"Optimizing Observations of Sea Ice Thickness and Snow Depth in the Arctic"

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LONG-TERM GOALS

This work is motivated by the desire to improve the quality of airborne and satellite-based measurements of sea ice thickness and snow depth in the Arctic; to achieve a resolution that is adequate for monitoring decadal variability and to minimize the degree of uncertainty in predictive models.

OBJECTIVES

The specific objectives of our proposed work are:

- To carefully assess remotely-based observations of Arctic sea ice thickness and snow depth using a rare set of coordinated in situ, airborne, satellite and submarine measurements collected by US Army Corps of Engineering Cold Region Research and Engineering Laboratory (CRREL), Naval Research Laboratory (NRL) and National Aeronautics and Space Administration (NASA) in conjunction with the US Navy at the ICEX2011 sea ice field camp in March 2011 in the Alaskan Beaufort Sea;
- To leverage and integrate the measurements and results from this focused effort with data collected during related national and international activities (e.g. NASA IceBridge sea ice missions, NRL under flights of CryoSat-2, European Space Agency (ESA) CryoVEx, submarine ice draft measurements, Alfred Wagner Institute (AWI) POLAR5 and historic ICESat records);

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- To use these data to revise error estimates of remotely-derived snow depth and thickness data products from, for example, ICESat, IceBridge and CryoSat-2. These error estimates (a) are critical for understanding the variability and trends in the long-term time series of observations, (b) will help tie the various satellite and airborne records together, and (c) provide important input for predictive sea ice models.

APPROACH

The paramount transformative aspect of this work is the combined application of coincident ice thickness and snow depth measurements collected in March 2011 [*Gardner et al*., 2012, Table 1]. The suite of measurements was strategically organized around a 9-km-long survey line that covered a wide range of ice types, including refrozen leads, deformed and undeformed first year ice, and multiyear ice. The data set consists of coincident in situ field measurements of snow depth and ice thickness taken by the CRREL/NRL field team; airborne laser altimetry measurements of the surface elevation of the snow or ice/air interface, and radar altimetry measurements of the snow/ice interface, taken by NASA IceBridge and NRL airborne teams [*Gardner et al.*, 2012]. This suite of data provides the full spectrum of spatial sampling resolution from satellite, to airborne, to ground-based, and will allow for a careful determination of snow depth on sea ice and sea ice thickness distributions.

The initial focus of our work was to process the CRREL, NASA and NRL data collected during the March 2011 field campaign. Once all discriminators and calibrations were in place, we extended our data analysis process to an intercomparison between NASA and NRL airborne datasets to the CRREL/NRL in situ data collected along the ICEX survey line. We will further leverage and integrate these data with other related activities and archives. During March/April 2011 this includes airborne measurements gathered at a variety of locations around the Arctic Basin during the PAMARCMiP POLAR5 campaign; the satellite, airborne and in situ observations made during CryoVEx, north of Alert to validate sea ice observations from the CryoSat-2 satellite; and the other NASA IceBridge sea ice surveys. We will also tap into relevant historical data sets. For instance, we will compare data collected in the Southern Beaufort and Lincoln Seas gathered during the IceBridge and PAMARCMiP 2009 to 2011 experiments, focusing on analysis of flight lines with near-spatial coincidence. This comparison will allow a detailed assessment of IceBridge and PAMARCMiP ice thickness estimates over seasonal sea ice (Southern Beaufort Sea) and heavily deformed multi-year ice (Lincoln Sea).

Our culminating objective is to use results from the proposed work to revise error estimates of remote snow depth and thickness data products, as a function of ice type. This advancement will reduce the level of uncertainty in the observational records of sea ice trends and variability and, hence, increase our understanding of the complex interaction between the atmosphere, ice and ocean in the Arctic region. It will also help us to tie the ICESat, ICESat-2 and CryoSat-2 records together to provide a long-term time series, improving a critical resource for predictive sea ice models.

WORK COMPLETED

A comparative analysis of the data collected during the March 2011 field campaign in conjunction with ICEX2011 was the focus of Year 1, while in Year 2 the focus was an analysis of related NASA IceBridge (e.g. sea ice flights) data collected during other elements of the March and April 2011 campaign. The list of work completed follows the proposed milestones and timeline (referenced to March 2012, project commencement):

- 12 months (March 2011): Sea ice field experiment at the ICEX 2011 Beaufort Sea ice camp. Acquisition of in situ, airborne and satellite data over Beaufort Sea ice pack (Contributing parties: CRREL, NRL, NASA)

+ 0 months (March 2012): Initial assessment of data collected during field deployment (CRREL, U Maryland, NRL)

+ 6 months (Sept 2012): Synthesis of in situ and IceBridge and NRL airborne data sets collected during ice camp with preliminary data analysis. Generate maps of ice thickness and snow depth for ice camp survey region. (CRREL, U Maryland, NRL)

+ 6 months (Sept 2013): Complete initial report on ice camp activities to include a full description of in situ data collected and success of field campaign. Details reported to ONR Arctic and Global Prediction Program Office. (CRREL, U Maryland, NRL)

+ 9 months (December 2012): Attendance at AGU Fall Meeting to present Year 1 results (Newman et al., 2012) and meet with international collaborators, laying the groundwork for Years 2 and 3 synthesis and coordination of future collaborative field programs (e.g. CryoVEx, AWI POLAR5).

+16 months (July 2013): Conduct detailed comparative analysis of CryoSat-2 data with in situ and airborne data to assess the accuracy and precision of CryoSat-2 Arctic sea ice elevation, sea ice freeboard, and derived thickness. Initial work has focused on simulation of the CryoSat-2 response in areas of level and ridged sea ice. (U Maryland, CRREL)

+18 months (Sept 2013): Prepare and submit publication of science results from Year 1 (U Maryland, CRREL).

RESULTS

During the first phase of this project we have focused on an assessment of the in situ data collected at the ICEX 2011 sea ice camp in the Beaufort Sea [*Gardner et al.*, 2012], and an intercomparison with coincident NASA IceBridge airborne measurements. In particular, we have concentrated our efforts on the issue of deriving accurate snow depth on sea ice. Snow depth uncertainty remains the largest source of error in deriving sea ice thickness from airborne/satellite altimeters. We have also augmented our analyses by including additional airborne and in situ data gathered during the European Space Agency's CryoVex 2011 experiment, which took place in April 2011 on thick, multi-year sea ice in the Lincoln Sea. Areas that have the thickest ice also have the most extreme ice topography, which makes the measurement of both snow depth and ice thickness especially challenging. Thus, the acquisition of the CryoVex 2011 data also allows us to conduct an assessment of how airborne and satellite altimeter estimates are affected by deformed sea ice surfaces.

The NASA airborne data consists of raw radar echograms from a snow radar, laser altimetry for surface topography and elevation, and visible digital photography for surface morphology. The primary in situ data comprise snow depth and sea ice thickness measurements. The airborne data have been quality assessed to check for geolocation and timing accuracy, and waveform anomalies (sidelobes) in the radar echograms have been identified. A novel wavelet-based technique that operates on the airborne snow radar echograms and provides automated snow depth retrievals has been developed (Figure 1). The maximum step in 'linear space' is assigned as the snow/ice interface, while the maximum step in 'logarithmic space' is assigned the air/snow interface. In tandem with the layer-

picking algorithm, we have developed a method to characterize and filter returns over severe ice surface topography, e.g. due to sea ice pressure ridges, that would otherwise lead to erroneous snow depths. Our snow depth results, which utilize data from both the ICEX and CryoVex 2011 experiments, are provided in Figure 1 and Table 1. We have compared the airborne snow radar snow depth estimates to the independent and coincident in situ data for both a thin snow case (ICEX) and a thick snow case (CryoVEx). Our analyses indicate that the airborne estimates of mean snow depth on level ice, after filtering pressure ridges, are accurate to within 2.5 – 3 cm (Table 1).

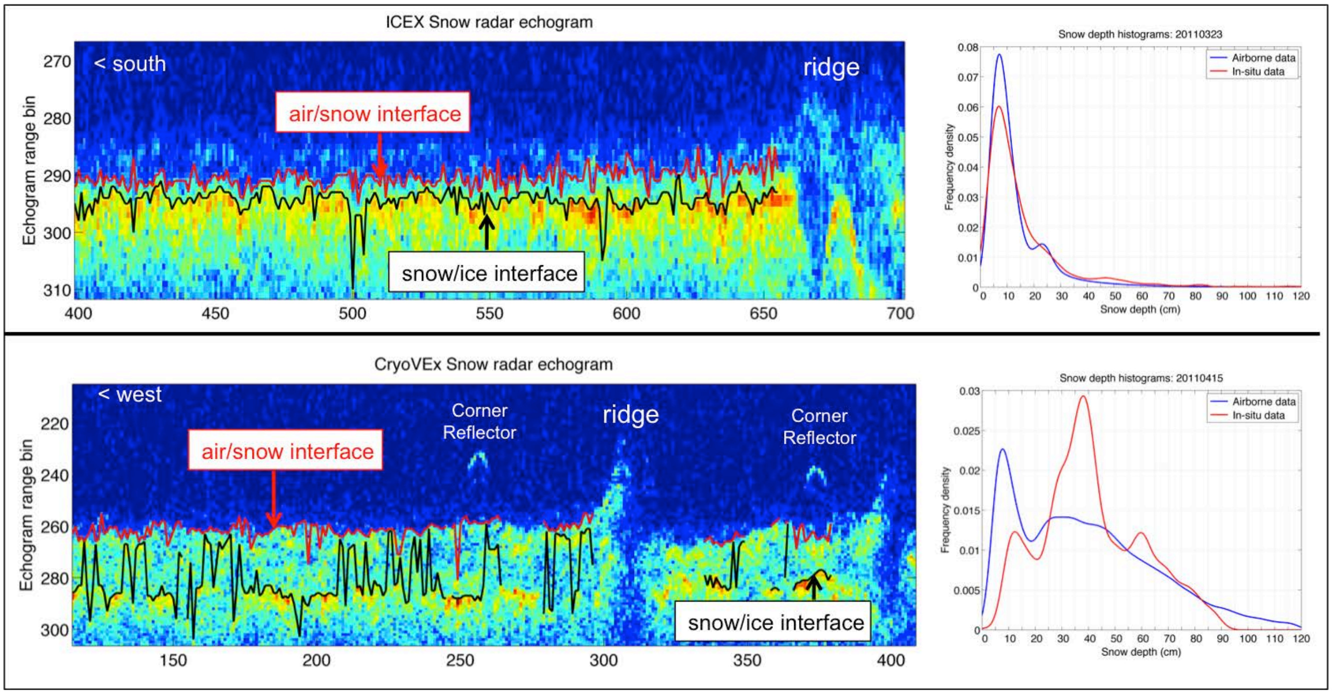

Figure 1. (Top) Snow-radar echogram collected during a NASA IceBridge flight on 23 March 2011 over the ICEX sea ice camp, in the Beaufort Sea and (bottom) on 15 April 2011 over the in situ CryoVex experiment in the Lincoln Sea. Annotations indicate the air/snow (red) and snow/ice (black) interfaces, defined using our automated layer-picking algorithm. (Right) Histograms of snow depth derived from the airborne sensors (blue line) and in situ snow depth measurements (red line). Results are provided in Table 1.

Table 1. Intercomparison of snow depth measurements collected in situ at two sea ice locations in March/April 2011 (top: ICEX 2011, Beaufort Sea; bottom: CryoVex 2011, Lincoln Sea) with snow depth estimates derived from IceBridge airborne snow radar echograms.

Snow depth on Sea Ice: ICEX 2011					
In Situ Data			Airborne		
Mean (cm)	Mode (cm)	Maximum (cm)	Mean (cm)	Mode (cm)	Maximum (cm)
15.5	6.9	120	13.1	7	118.9

Snow depth on Sea Ice: CryoVex 2011					
In Situ Data			Airborne		
Mean (cm)	Mode (cm)	Maximum (cm)	Mean (cm)	Mode (cm)	Maximum (cm)
41.4	38	160	38.7	7.8; 29.1	117.5

The results of this phase of the project are currently being prepared for submission to a peer-reviewed journal (Newman T., S. L. Farrell, J. Richter-Menge, L. Connor, N. Kurtz, B. Elder, D. McAdoo, An assessment of IceBridge data quality over Arctic sea ice via comparison with in situ measurements, *manuscript in preparation*).

IMPACT/APPLICATIONS

The revised error estimates of remotely-sensed snow depth and ice thickness observations generated by this investigation are critical for (1) understanding variability and trends in the long-term time series of NASA IceBridge observations, (2) tying the ICESat, ICESat-2 and CryoSat-2 records together, and (3) providing important input for predictive ice models. More specifically, the comparative study between the in situ data sets and coincident airborne and satellite data acquisitions will improve the understanding of new sensors. These include the Kansas snow radar, the NRL radar altimeter, and CryoSat-2's SIRAL radar altimeter. Recently, for example, the NASA IceBridge observations were used to validate of sea ice thickness estimates from CryoSat-2 [*Laxon et al.*, 2013].

Data collected at the ICEX 2011 ice camp include measurements of first and multiyear ice. Based on the work of *Farrell et al.* (2012) we expect to see differences, especially in accuracy, from several of the instruments both at the transition zone between these ice types and in the multiyear ice where interpretation of radar data over heavily deformed ice is more challenging. This will allow us to better assess each sensor's capabilities as a function of ice type. This knowledge will be applied to aid in the interpretation of the entire NASA IceBridge data set. The results will also influence future sensor, and sensor suite, development and provide a metric for combining/contrasting future dataset collections. Incorporating knowledge of these measurements and their accuracy into new algorithms will support improvements in regional sea ice models.

Figure 2 shows pan-Arctic snow depths derived from IceBridge data as part of this ONR-funded research. The results demonstrate the divergence in contemporary snow depth on seasonal sea ice,

from the historical climatology developed by *Warren et al.* (1999). This result has implications for the algorithms used to infer sea ice thickness from satellite altimetry measurements, since they typically rely on the snow depth climatology of *Warren et al*. (1999) as an auxiliary input.

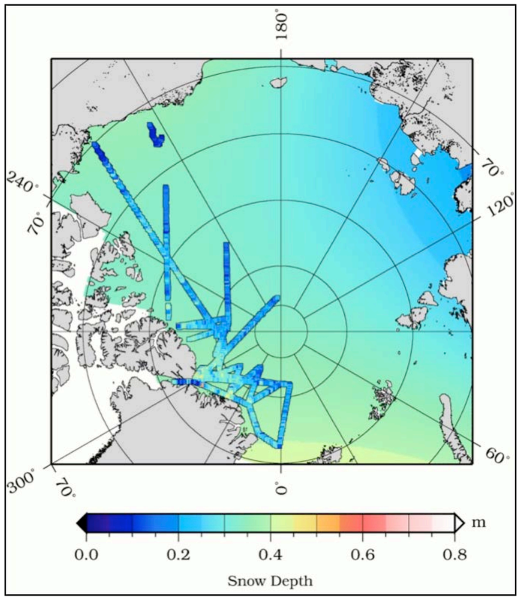

Figure 2. Intercomparison of snow depth derived from IceBridge snow radar data with a snow depth climatology [Warren et al., 1999]. The IceBridge snow depths were derived using the novel snow picking technique applied to data collected in March/April 2011, and span the Western Arctic basin. We find good agreement between the climatology and airborne-derived snow depths north of Greenland and Ellesmere Island over multi-year ice. Elsewhere the airborne snow depths diverge from the climatology. We find that snow depths on first year ice are ~50 % thinner than predicted in the climatology. This has important implications for the algorithms used to derive sea ice thickness from satellite altimetry measurements.

RELATED PROJECTS

- NOAA: "Towards Operational Production of Arctic Snow and SEa ice Thickness (TOP - ASSET)" is supported under the NOAA/NESDIS/STAR/SOCD Ocean Remote Sensing Program and is conducted in collbaoraiton with NASA IceBridge and CRREL. It continues to support the collection and reduction of a long-term time series of snow and sea ice thickness data in the Arctic Ocean. The goal is to continue the legacy of previous Arctic airborne campaigns conducted since 2002 to gather high-reoslution altimetry over both seasonal and multi-year ice floes. These high-resolution datasets are used as a calibration and validation tool to assess satellite altimetery measurement accuracy from Envisat, ICESat and CryoSat-2.

- NASA IceBridge. The NASA IceBridge project is closely related, having participated in the March 2011 field campaign with airborne survey flights over the 9-km ground line used to collect in situ snow and ice thickness data. NASA's Operation IceBridge mission utilizes a highly specialized fleet of instrumented research aircraft to characterize annual changes in thickness of sea ice, glaciers, and ice sheets. These observations are being applied to predict the

response of earth's polar ice to climate change and resulting sea-level rise. IceBridge also helps bridge the gap in polar observations between NASA's ICESat satellite missions.

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